

# Shear Stress Measurements via Elastomeric Micropillar Arrays

*Dr. Christopher J. Wohl*, Advanced Materials and Processing Branch, NASA LaRC

*Dr. Frank L. Palmieri*, Advanced Materials and Processing Branch, NASA LaRC

*Dr. John W. Connell*, Advanced Materials and Processing Branch, NASA LaRC

*Dr. Yi Lin*, National Institute of Aerospace (NIA)

*Allen Jackson*, Fabrication Technology Development Branch, NASA LaRC

*Alexxandra Cisotto*, NASA Langley Aerospace Research Summer Scholars Program, NASA LaRC

*Dr. Mark Sheplak*, Interdisciplinary Microsystems Group, University of Florida

ARMD NARI 2012 Seedling Phase I Review

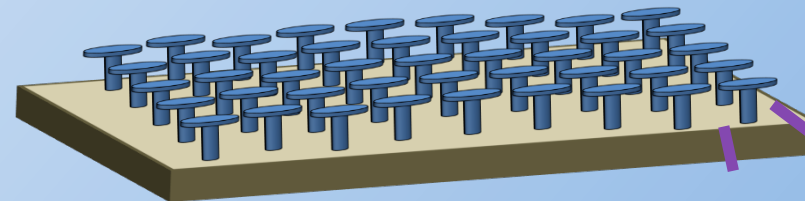
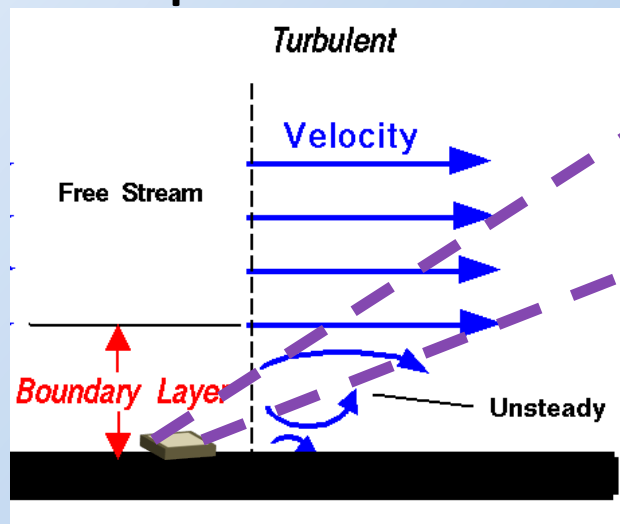
July 9-11, 2013

# Technical Objective

NASA Aeronautics Mission Directorate FY12 Seedling Phase I Technical Seminar

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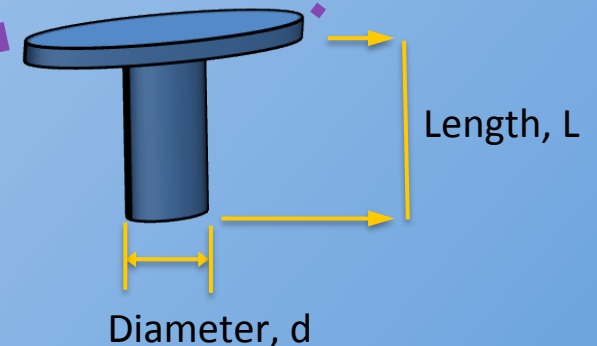
- The objective of this work is to generate a robust shear stress sensor capable of **making accurate shear stress measurements up to 10 Pa with  $\mu\text{Pa}$  sensitivity** without airflow disruption.



$$\tau = \eta * \left. \frac{\partial U}{\partial y} \right|_{wall}$$

Within the viscous sub-layer

$$\tau = \eta * U / y$$

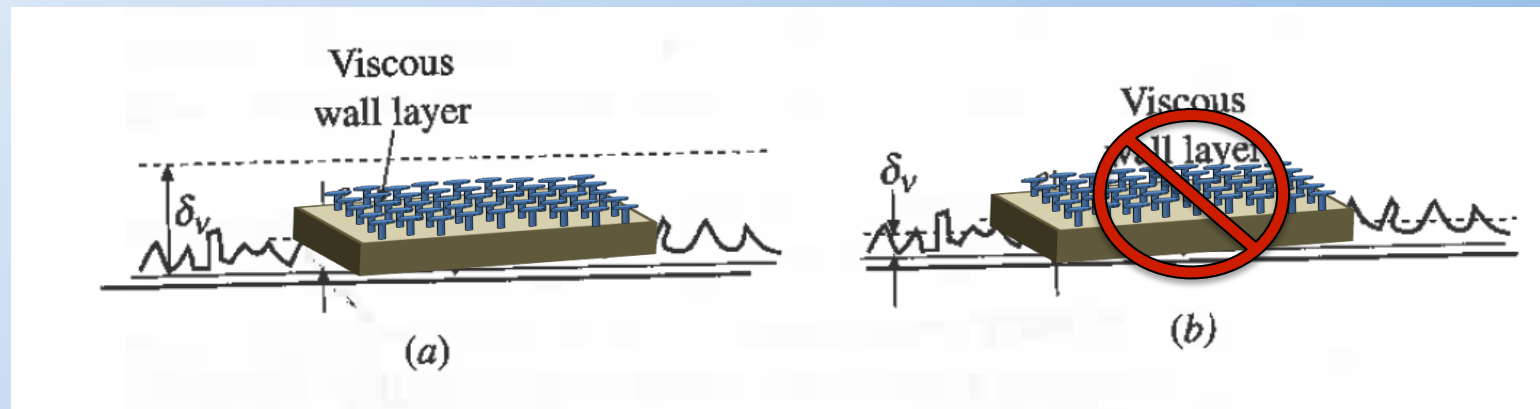


# Technical Objective

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- The objective of this work is to generate a robust shear stress sensor capable of making accurate shear stress measurements up to 10 Pa with  $\mu\text{Pa}$  sensitivity **without airflow disruption.**



A Smooth Wall

A Rough Wall

Image from: Potter, Merle C. Fluid Mechanics Demystified. The McGraw Hill Company, New York, 2009, p. 144.

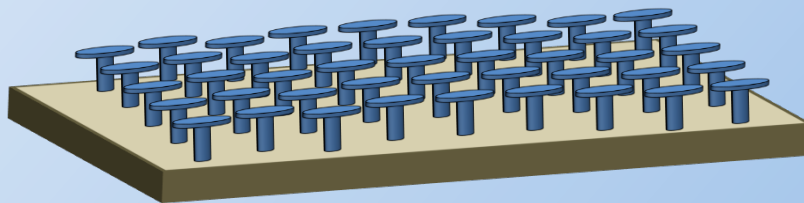


# Technical Approach

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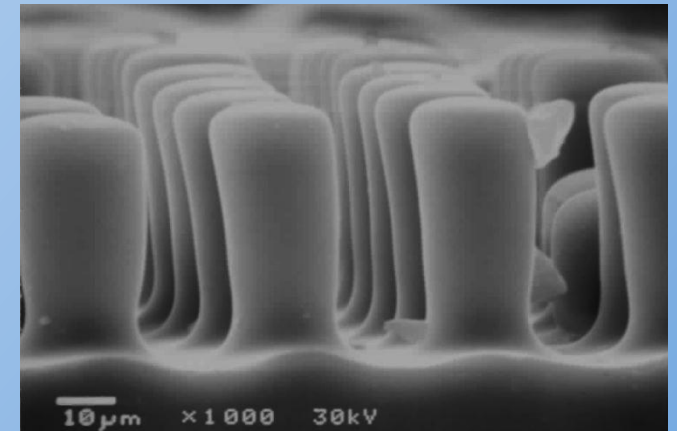
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- Phase I: Pillar Array Design and Fabrication
  - Generate master templates using available lithographic processes  
Identify requisite pillar parameters for shear stress measurements in subsonic flows
    - Laser ablation of epoxy substrates
    - Contact lithography of SU-8 coated Si Wafers
  - Fabricate micropillar arrays using commercially available elastomeric materials
- Phase II: Pillar Calibration and Signal Transduction
  - Calibrate pillar deflection using atomic force microscopy
  - Determine signal transduction approach



Concept

Pillar Parameter	Value
Length, $L$	$L < 100 \mu\text{m}$
Aspect Ratio, $L/d$ (diameter)	$L/d \geq 3$
Pillar Spacing, $s$	$s > 2L$
Deflection Limit, $w$	$w \leq 0.1L$



Current Status



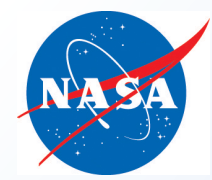
# Impact if Successful

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Current shear stress measurement techniques that minimally impact airflow are difficult to implement, of questionable reliability, and sensitive to environmental factors.

- Development of the proposed sensors would alleviate many of these issues enabling shear stress measurement on a variety of surfaces including acoustic liner applications with sensors that:
  - Are robust
  - Reduce complexity for model integration
  - Enable measurement in 360°
- The most promising signal transduction technique may be amenable to existing technologies utilized in Particle Image Velocimetry (PIV) measurements conducted in wind tunnels.

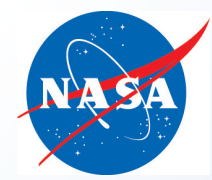


# Distribution/Dissemination

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- Invention Disclosure/Provisional Patent Application: Palmieri, Frank P.; Wohl, Christopher J.; Connell, John W.; Sheplak, Mark. Shear Stress Sensing using Elastomer Micropillar Arrays, LAR-18336, 2013
- 2012 NASA Nanotechnology Report
- Symposium titled, “Sensing and Controlling Motion using Polymeric Materials” at the 246<sup>th</sup> American Chemical Society National Meeting, Sept. 8-12, 2013 in Indianapolis.
- Wohl, Christopher J.; Palmieri, Frank L.; Lin, Yi; Jackson, Allen M.; Cisotto, Alexxandra, A.; Sheplak, Mark; Connell, John. W. Shear Stress Sensing using Elastomer Micropillar Arrays, 246<sup>th</sup> ACS National Meeting, Indianapolis, IN, Sept. 8-12, 2013.



# Accomplishments

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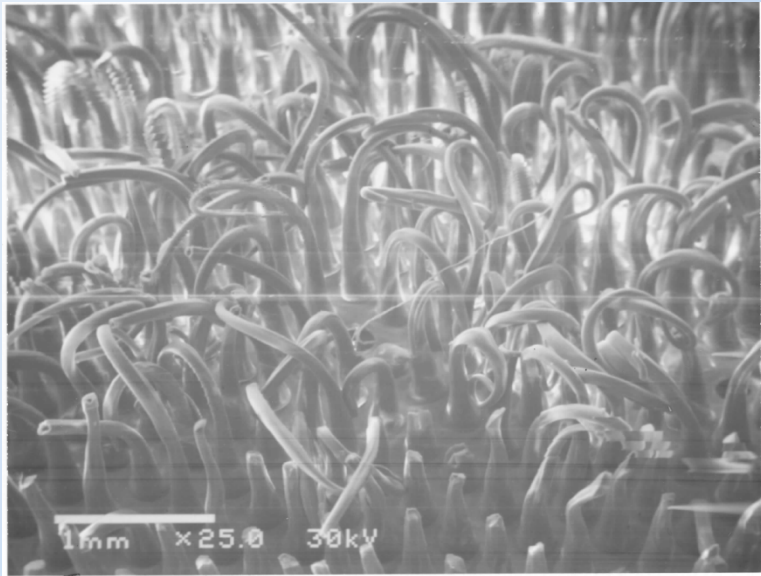
- Milestones:
  - Phase I:
    - M1: Fabricate micropost arrays
    - M2: Generate macroscopic example of concept
  - Phase II:
    - M3: Fabricated “capped” micropost arrays
    - M4: Determine nanopost array mechanical properties
    - M5: Identify and implement signal transduction method

# Accomplishments

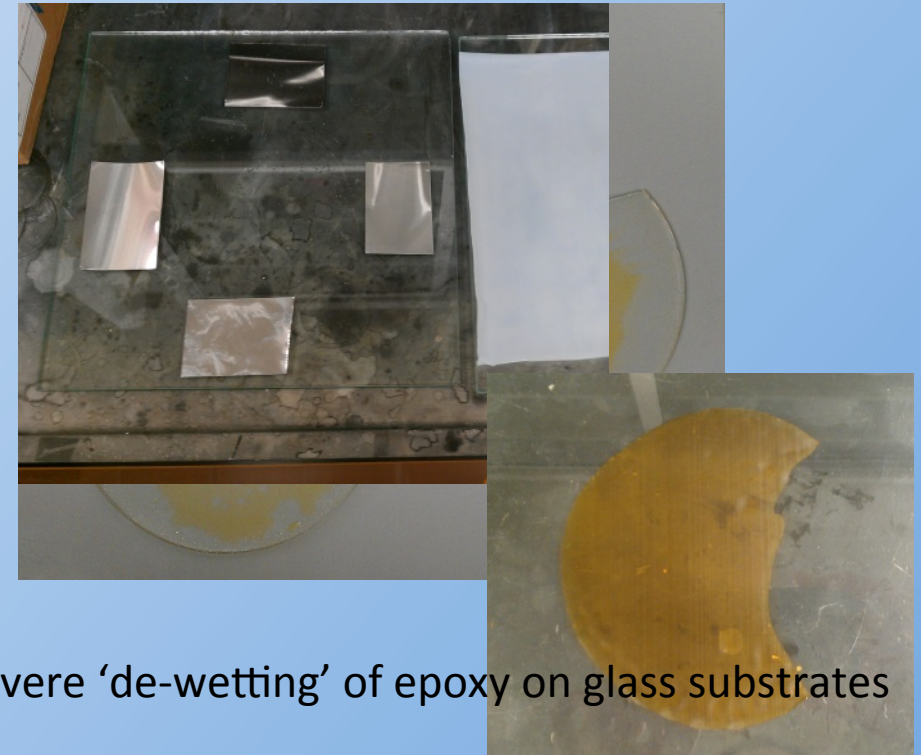
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- M1: Generation of master templates amenable to micropillar array fabrication: laser ablation patterning



PDMS mold of laser ablated epoxy coupon



Severe 'de-wetting' of epoxy on glass substrates

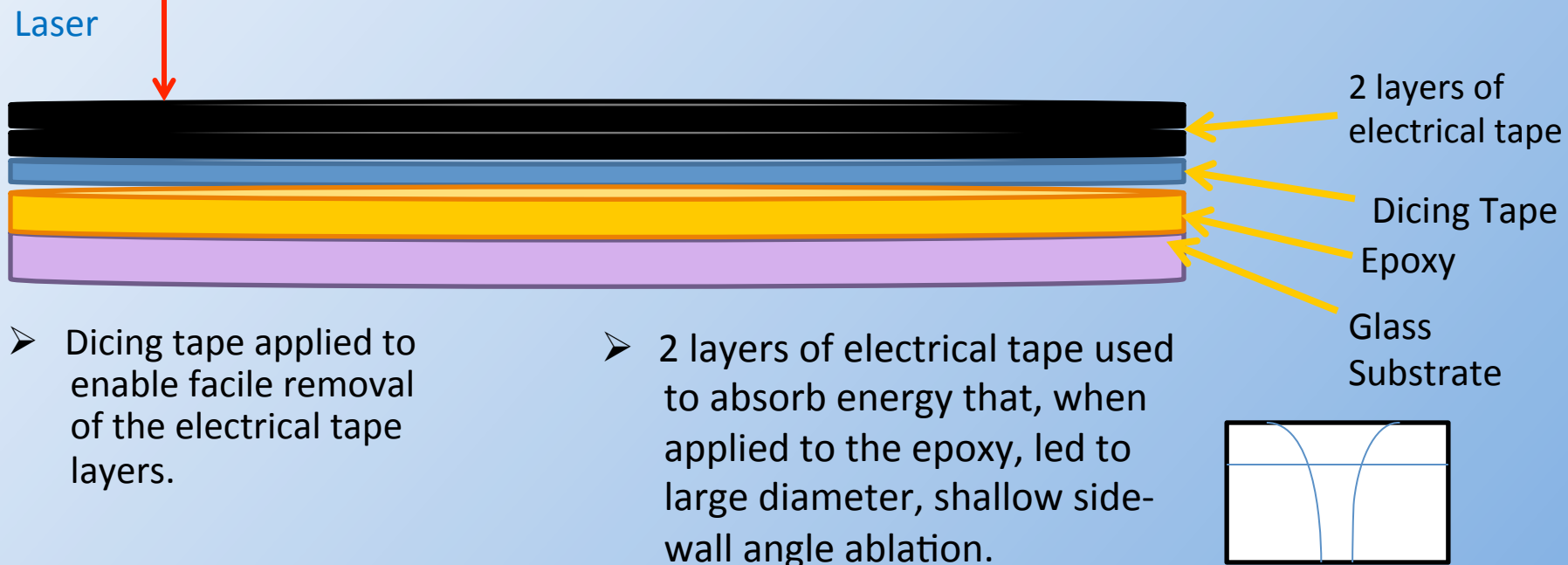


# Accomplishments

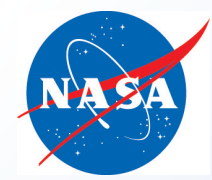
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- M1: Generation of master templates amenable to micropillar array fabrication: laser ablation patterning



Laser ablation patterning affords excellent depth control but has limited diameter control with a minimum achievable diameter of approximately 35  $\mu\text{m}$ .

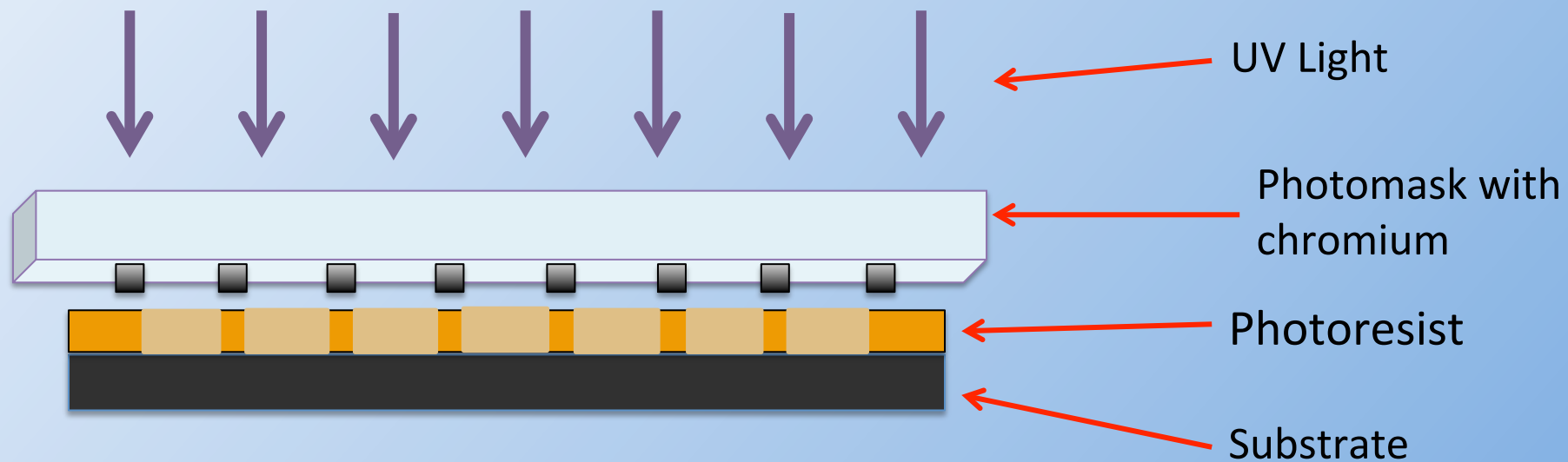


# Accomplishments

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- M1: Generation of master templates amenable to micropillar array fabrication: contact lithography



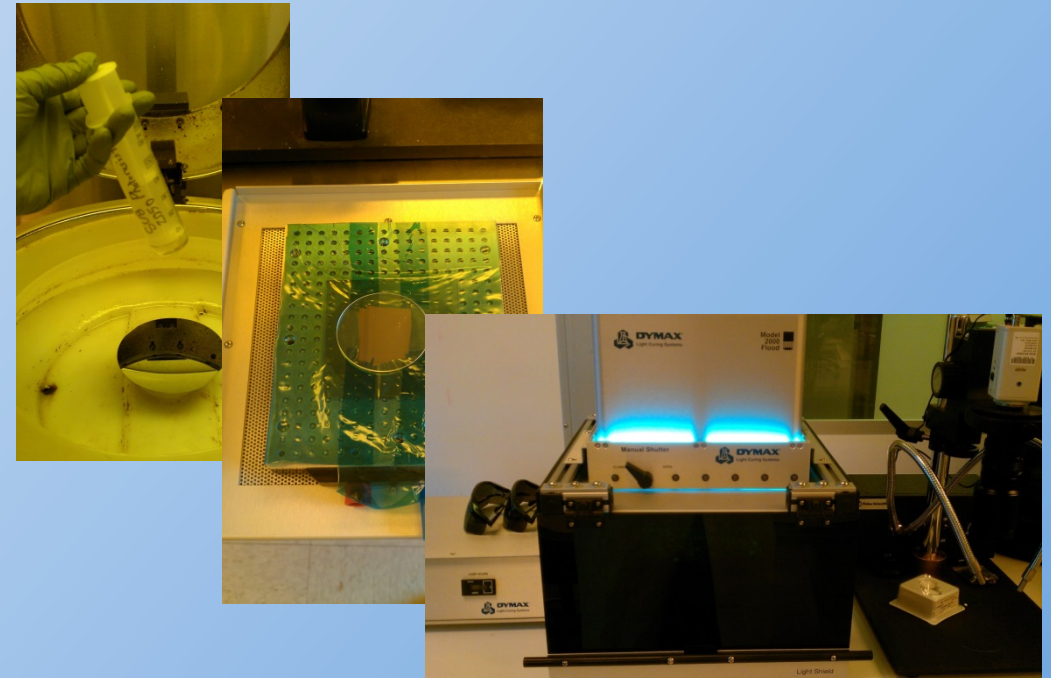


# Accomplishments

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- M1: Generation of master templates amenable to micropillar array fabrication: contact lithography
  - This procedure required process refinement for several steps:
    - Plasma exposure of Si wafers
    - Dehydration baking
    - SU-8 adhesion promotion layer
    - SU-8 application
    - Soft bake
    - Photomask positioning and exposure
    - Pattern development

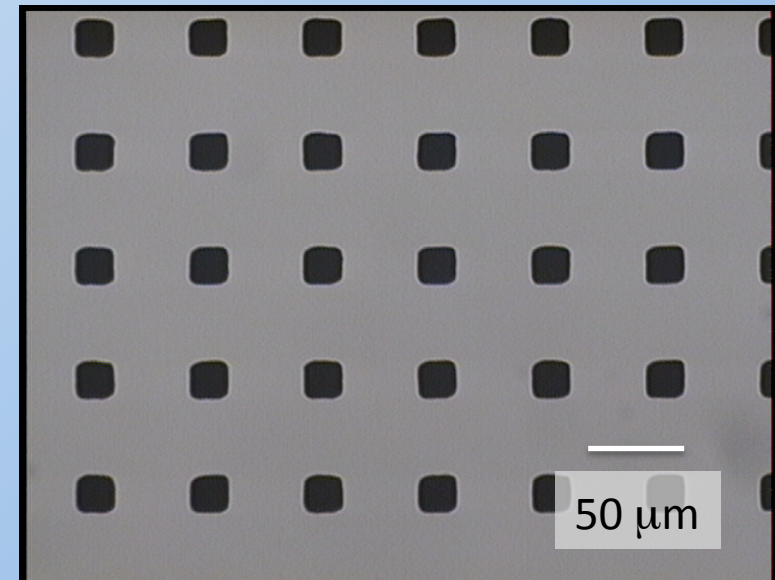
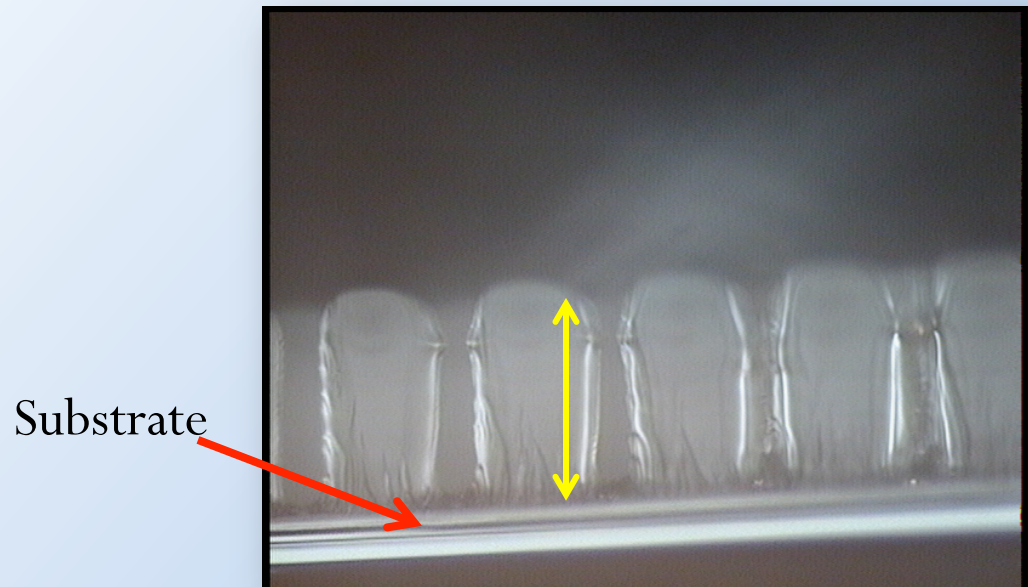


# Accomplishments

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- M1: Generation of master templates amenable to micropillar array fabrication: contact lithography



Photolithography offers greater capability for increased aspect ratios relative to laser ablation patterning. However, the available photomask patterns are far too dense.

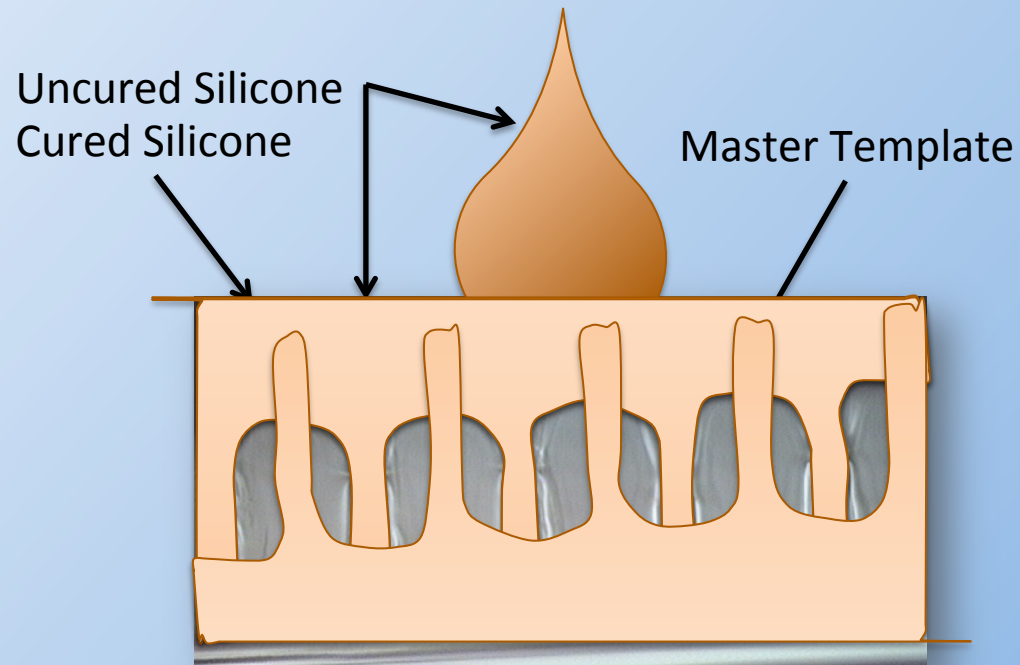


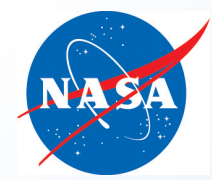
# Accomplishments

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NARI

- M1: Fabrication of micropillar arrays using soft lithographic techniques





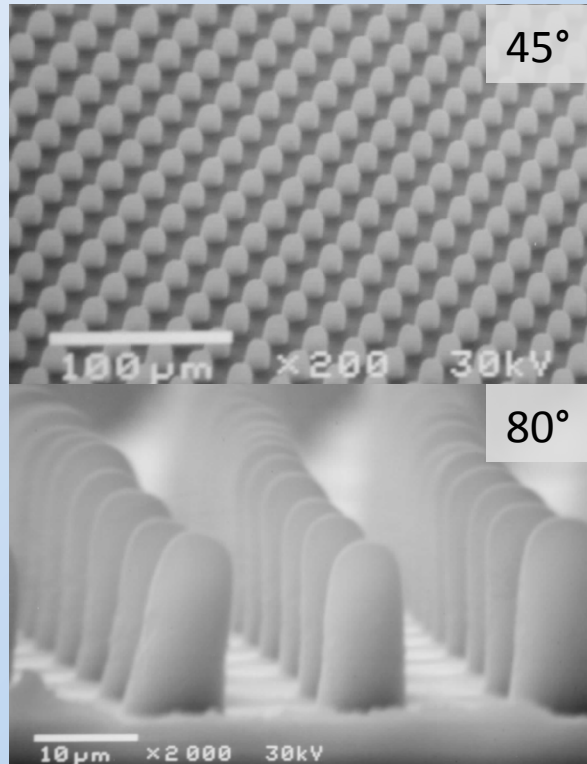
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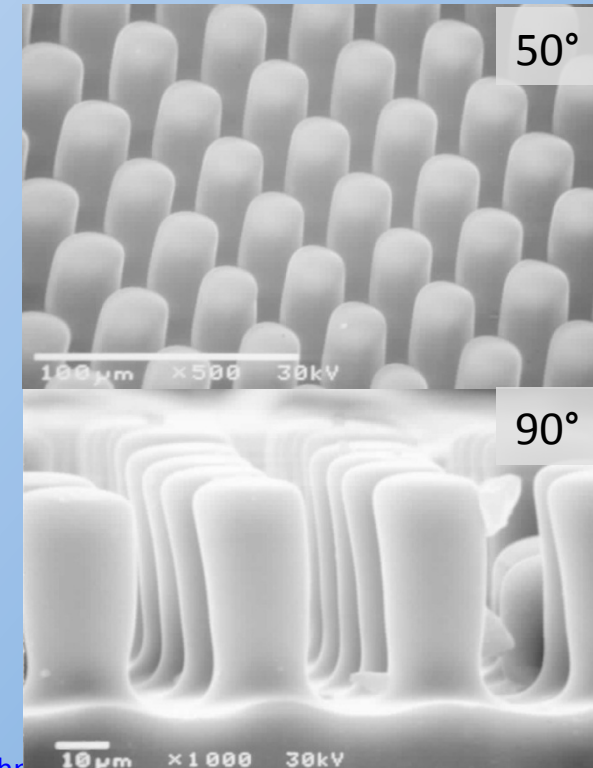
NARI

- M1: Fabrication of micropillar arrays using soft lithographic techniques: using contact lithography templates

Early samples  
15-20  $\mu\text{m}$



Recent results  
45-50  $\mu\text{m}$





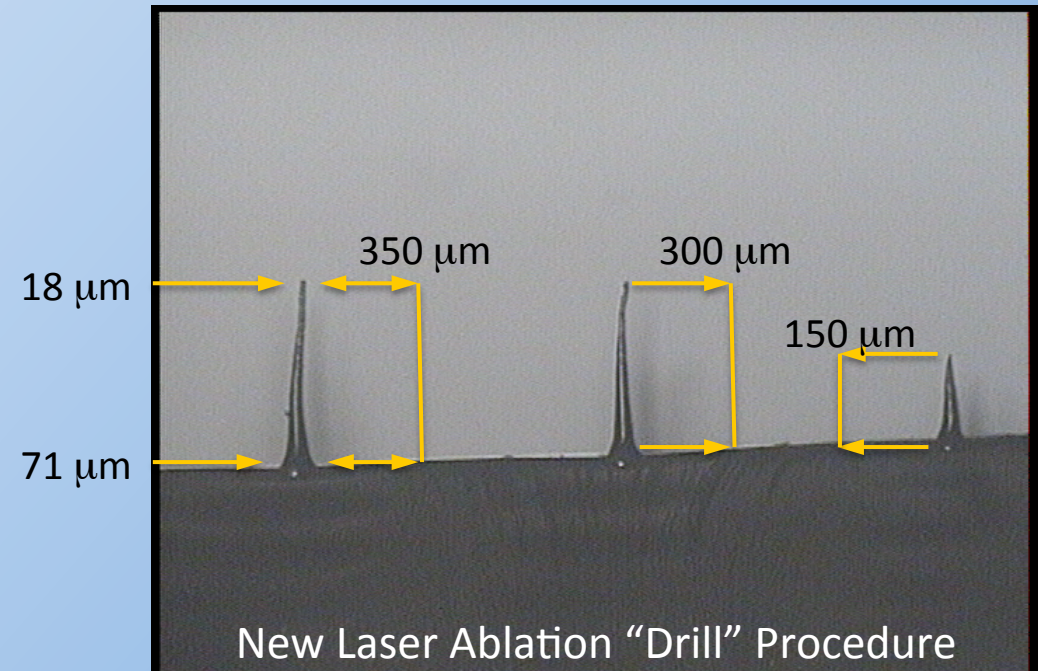
# Accomplishments

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- M1: Fabrication of micropillar arrays using soft lithographic techniques: using laser ablation generated templates

% power	kHz	in/s	Post Height ( $\mu\text{m}$ )
90	60	2.5	115
90	60	2.0	123
92	60	3.0	62
92	60	2.5	45 - 85
92	60	2.0	132
95	60	3.0	85
95	60	2.5	123

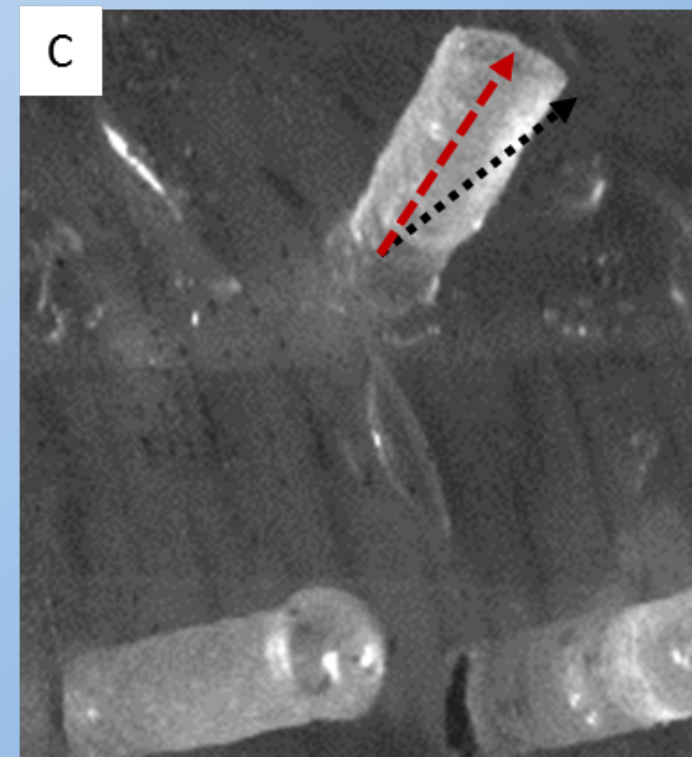
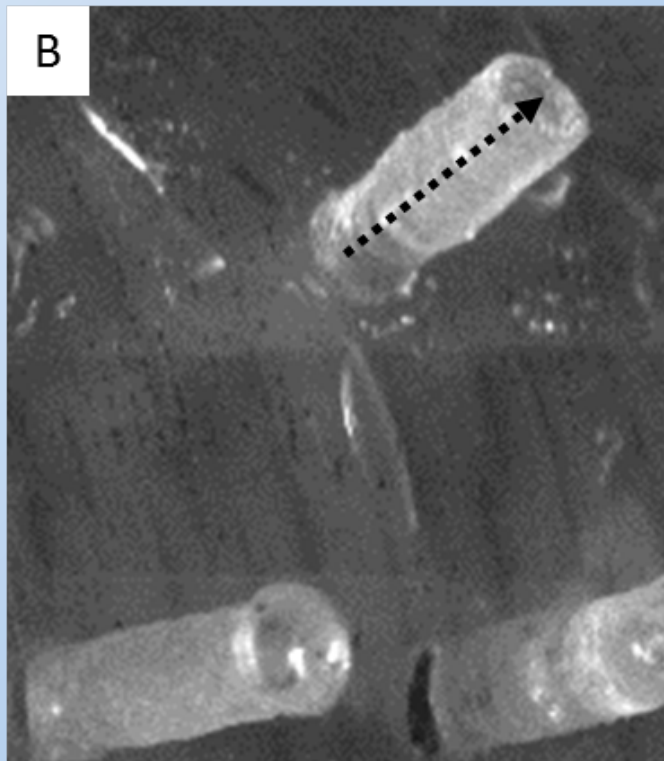


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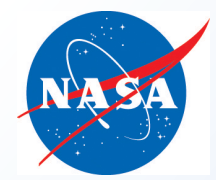
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- M2: Generation of a macroscopic example of the micropost array sensor



Pillar deflection was readily observed on the macroscopic sample.

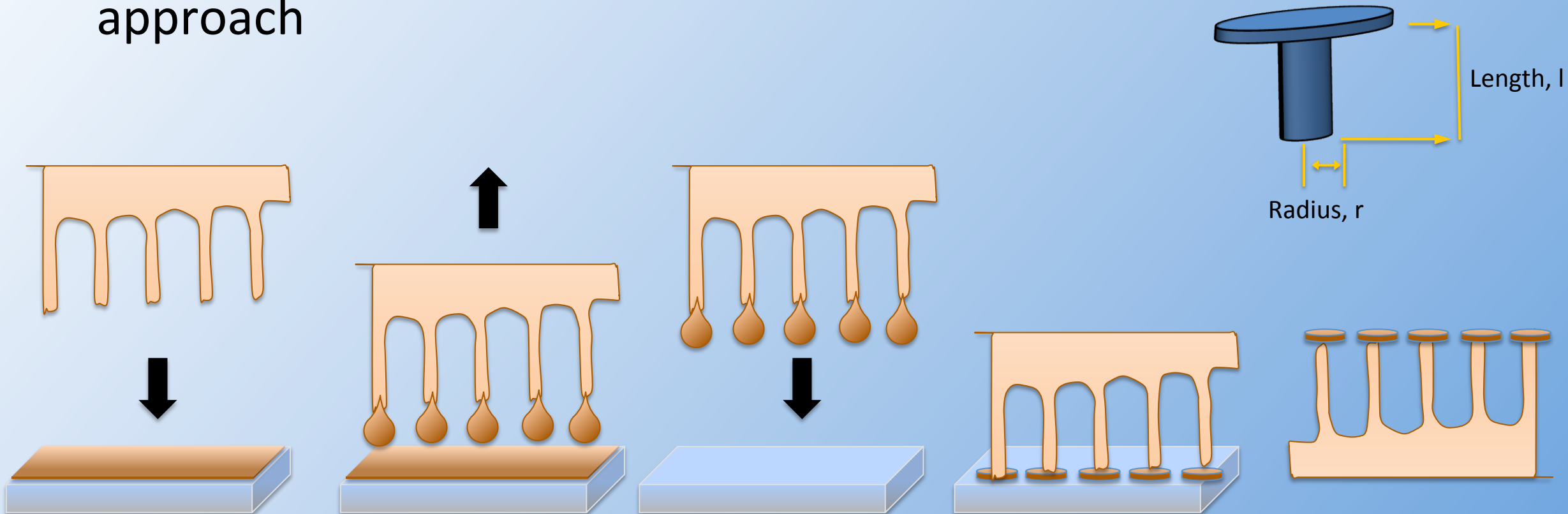


# Images of Preliminary Capping Efforts

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- M3: Fabrication of “capped” micropillar arrays: schematic of approach



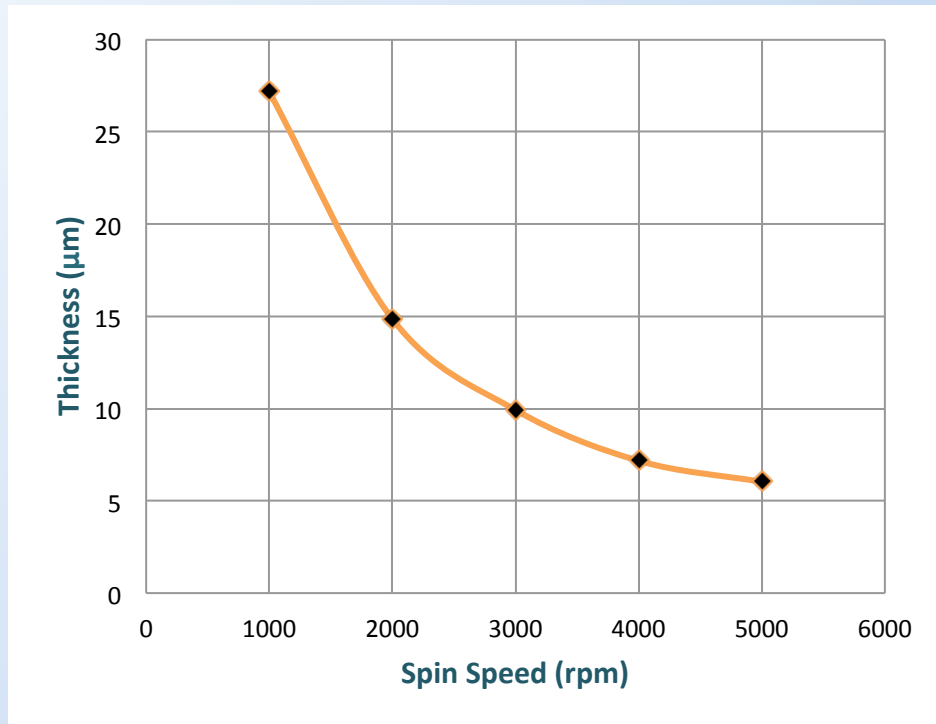


# Images of Preliminary Capping Efforts

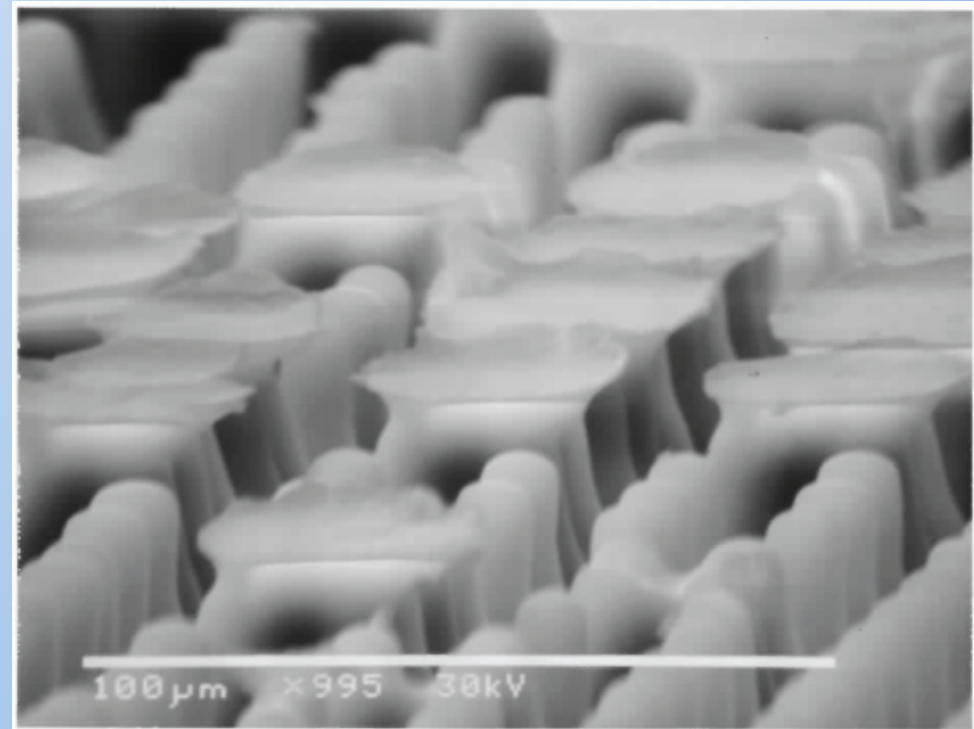
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## Sylgard Spin Curve



## SEM Image of “Capped” Pillars



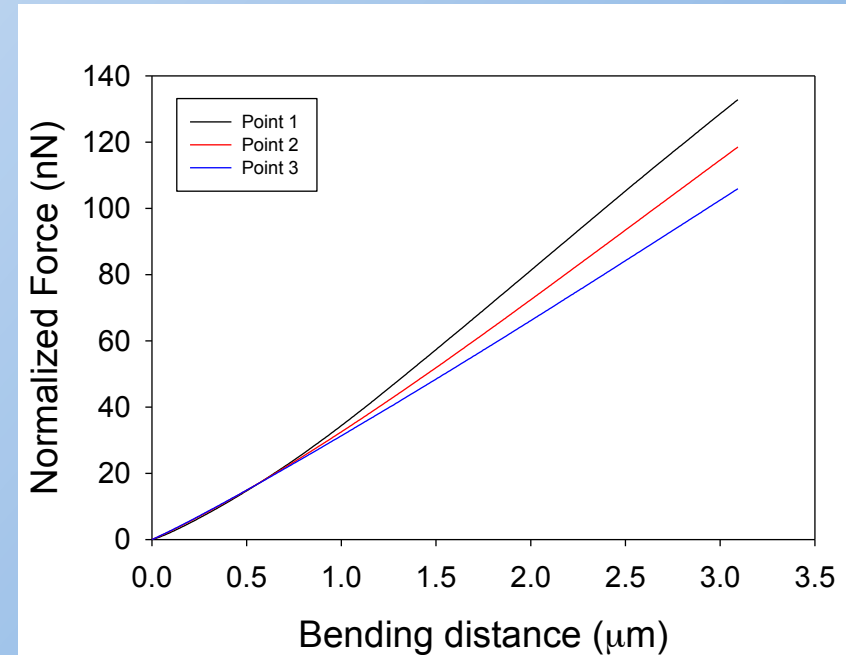
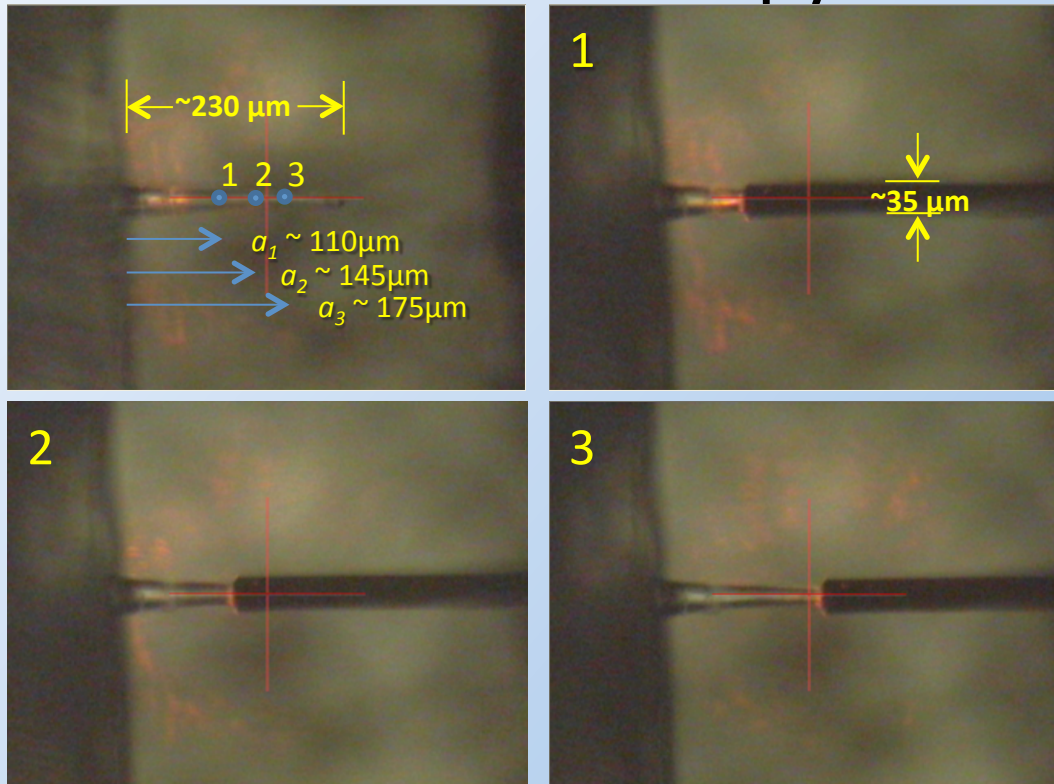
“Cap” film thickness can be easily varied based on spin-coater settings. With greater pillar spacing, the caps should readily form and be free standing, i.e., no pillar coupling.

# Accomplishments

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- M4: Force-displacement pillar calibration experiments using atomic force microscopy



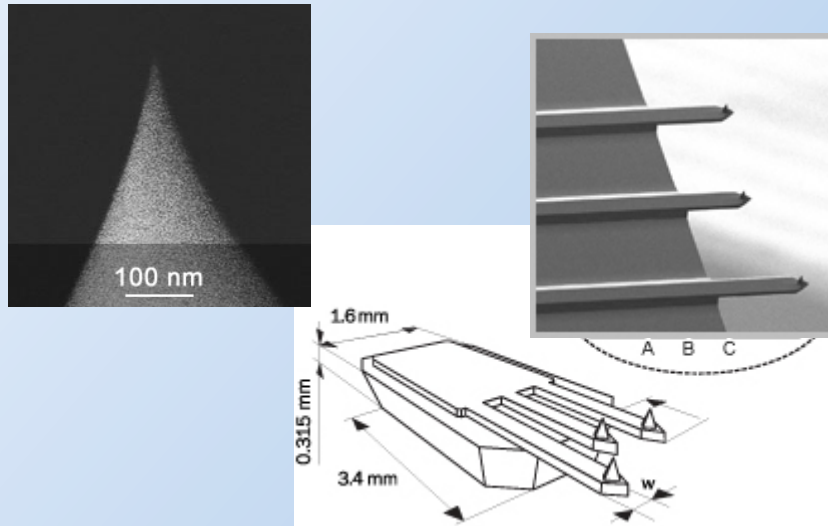
# Accomplishments

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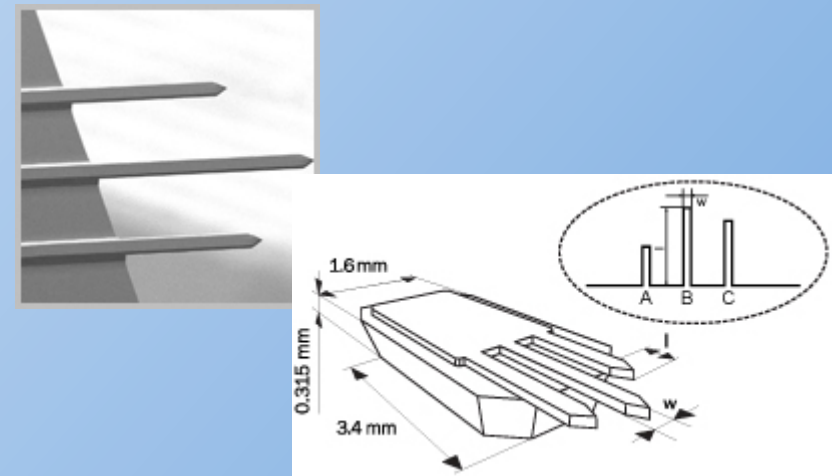
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- M4: Force-displacement pillar calibration experiments using atomic force microscopy

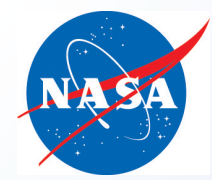
## 'Tipped' AFM Cantilever (NSC35/36)



## 'Tipless' AFM Cantilever (CSC37/38)



With tipless cantilevers, more representative and more precise data will be collected regarding pillar deflection forces.

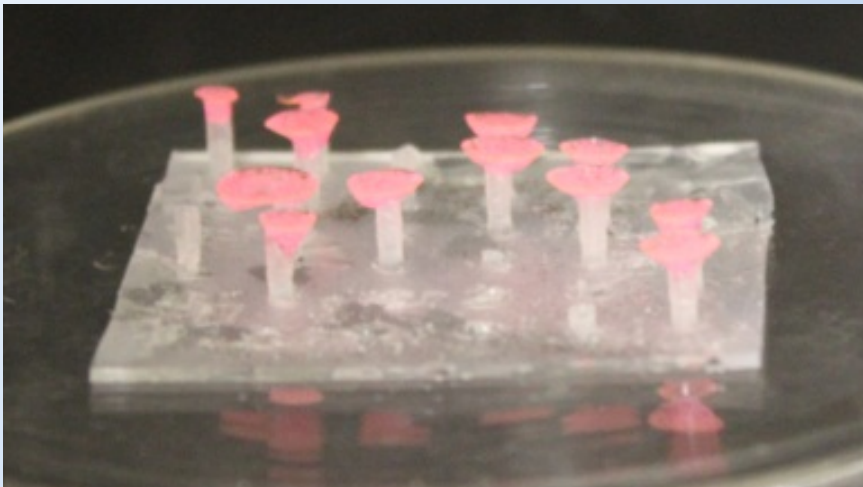


# Accomplishments

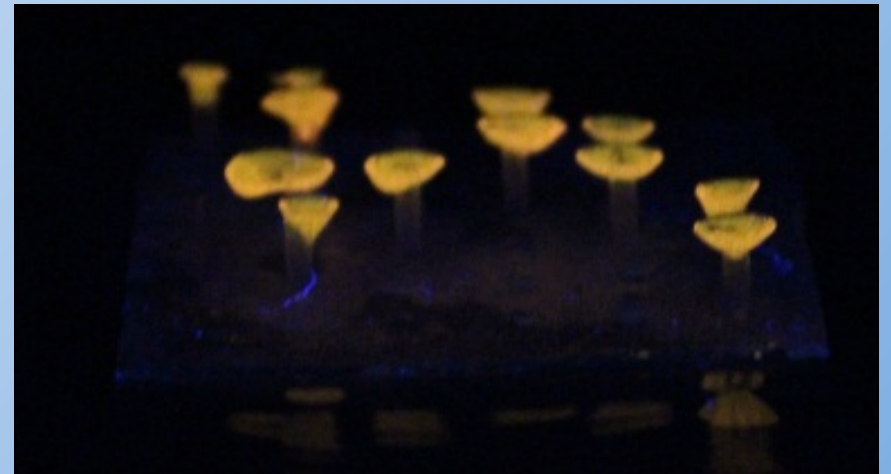
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- M5: Identification of most efficacious method for signal transduction: optical, piezoelectric, etc.

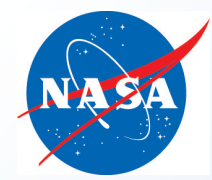


Visible Light Illumination



UV Light Illumination

Optical detection schemes enable current detection technologies for PIV measurements to be used for pillar deflection measurements.

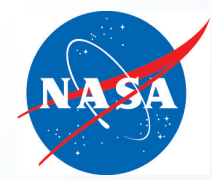


# Next Steps (Phase II Efforts)

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- Micropillar array design refinement
  - Identification of greatest efficacy methods for micropillar capping and signal enhancing dopant
  - Characterize micropillar deflection
  - Develop micropillar arrays for various wind speeds
- Interfacing with U of F in wind tunnel
  - Determine measurement range, sensitivity, noise floor, etc.
- Use of PIV equipment and visualization techniques to see pillar deflection
- Analysis of all fabrication, characterization and test results provided in a final report, recommendations for any future work needed that may lead to ARMD directed funding, or to next steps required to implement the technology into planned wind tunnel experimentation

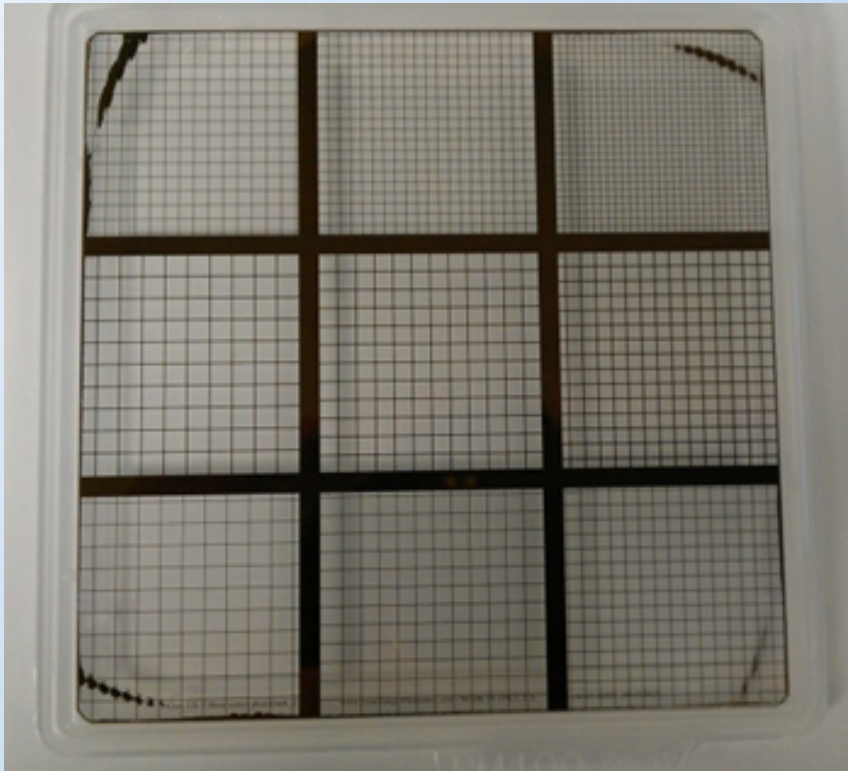


# Next Steps (Phase II Efforts)

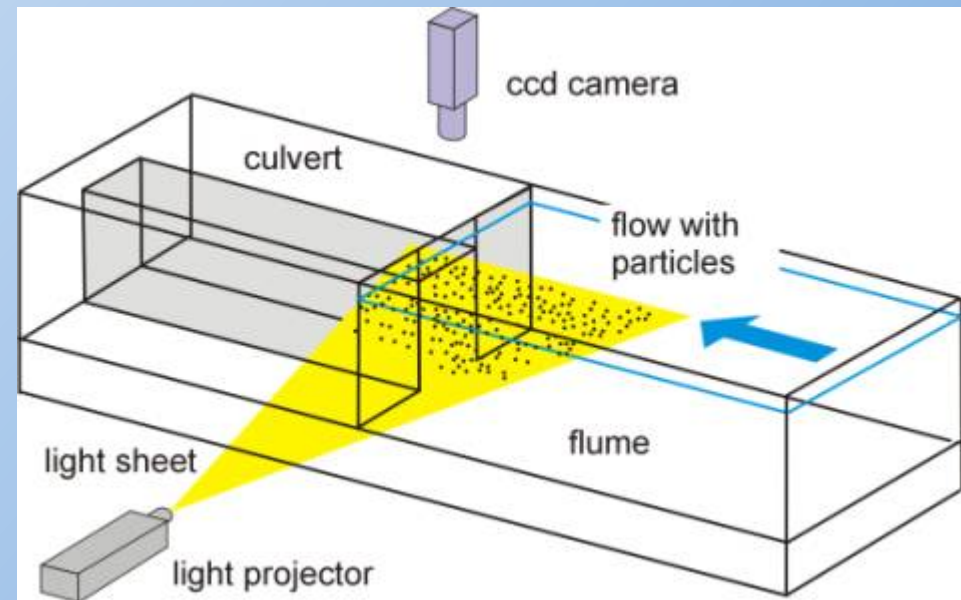
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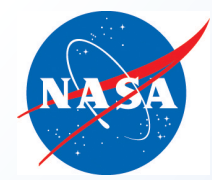
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## Designed Photomask for Contact Lithography Master Template Fabrication



## Integration of Micropillar Array Sensors with Existing (Micro) Particle Image Velocimetry Instrumentation





# Phase I Accomplishments

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- Procurement funding utilized to:
  - Fund a USRP student in the Spring of 2013 and a Langley Aerospace Research Summer Scholar (LARSS) in the Summer of 2013
  - Partially fund a new post-doctoral contractor to develop novel template materials for laser ablation master development
  - Procure lithography process equipment that is now available to all of LaRC
  - Travel down to University of Florida to solidify Phase II planning with Mark Sheplak (Interdisciplinary Microsystems Group)
    - Travel to U of F also resulted in potential collaboration with another researcher in the Department of Chemistry (Kirk Schanze) regarding novel seed material for airflow visualization
- Research efforts have led to:
  - Submission of an invention disclosure and provisional patent application: LAR 18336, Shear Stress Sensing Using Elastomeric Micropillar Arrays
  - Initial development of a Space Act Agreement with Mark Sheplak (U of F)
  - Generation of a clear path for Phase II research plans involving initial sensor evaluation, design refinement, and implementation
- Organization of a symposium at the 246<sup>th</sup> ACS National Meeting in Indianapolis, IN titled “Sensing and Controlling Motion with Polymeric Materials.” Co-organizer, Michael Dickey, North Carolina State University, Department of Chemical and Biomolecular Engineering.



# Supplementary Slides

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# State-of-the-Art Shear Stress Sensing

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## Indirect Measurements

- Hot Wire Anemometer
- Pitot Tube
- Whispering Gallery Mode

## Direct Measurements

- Oil Interference
- MEMS devices